Plio–Pleistocene raised channel systems of the western Sharqiya (Wahiba), Oman

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SUMMARY: Extensive alluvial fans bounding the western edge of the Sharqiya (or Wahiba) Sands are characterized by complex palaeochannel systems now forming a series of superimposed gravel ridges. The oldest, most extensive fan system is crossed by numerous sinuous, superimposed palaeochannel courses comprising highly weathered, chert-rich gravels cemented by clear crystalline calcite. Many of these old fan sediments have been chemically altered to depths of over 200 m to form a pink dolomitic clayey deposit here termed barzamanite. The formation of this calcrete-like deposit was probably associated with rising water tables during long-term fan growth. The younger, more limited fan deposit, by contrast, comprises thin, coarse-grained, broad spreads and terrace veneers of weakly cemented ophiolitic gravels. The fans have been subject to entrenchment and deflation, resulting in extensive land-surface lowering and the exhumation of buried palaeochannels. Although no dates are yet available, the older channel systems are likely to date from more humid phases during the Pliocene–Early Pleistocene, whereas the younger, terraced deposits, and the period of subsequent channel exhumation, may date from semi-arid periods of lower sea level during the Pleistocene.

The Eastern Oman Mountains are flanked on their southern margins by alluvial fan deposits, extending for distances of over 200 km, and bounding the western edge of the Wahiba sand sea and its associated aeolianite. The former alluvial stream deposits now form complex systems of 'raised' or upstanding, sinuous, superimposed linear ridges and broad gravel sheets, rising 10–20 m above the surrounding plains, producing an extensive area of inverted drainage (Figs 1 and 2).

This study aimed, firstly, to develop a model of palaeoenvironmental change and landscape development for the area of 'raised' channels. Secondly, the study aimed to identify the likely palaeohydrologic and palaeoclimatic conditions associated with periods of channel formation, fan aggradation and erosion. The final objective was to provide an overall chronological framework for these palaeoenvironmental changes in relation to the Wahiba and to the Arabian peninsula during the Quaternary.

Previous research

No detailed field investigation has previously been made into the exhumed palaeochannel systems W of the Wahiba, although there are a number of descriptions of similar raised channel deposits recorded elsewhere. Workers in Arabia and North Africa have introduced a number of different terms to describe such channels. Miller (1937) described the channels as 'suspendritic drainage lines' that stood out in 'bas-relief' above the surrounding plains in eastern Saudi Arabia. Knetsch (1954) used the unfortunate term 'pseudo-esker' to describe the sinuous gravel ridge features of the Dakka Basin in Saudi Arabia. Other workers have described these 'gravel-capped ridges' in the western Transvaal (King 1942) as 'gravel trains' (Holme 1960; Brown 1960 in Beydoun 1980), as 'perched wadis' or 'wadi ridges' in Egyptian Nubia (Butzer & Hansen 1968), as 'suspenparallel drainage' in W Texas and New Mexico (Reeves 1983), and as 'raised channels' (Warren *et al.* 1985). Less ambiguous definitions have been provided for the Omani palaeochannel systems by Glennie (1970) who describes them as 'ridges of exhumed Pleistocene (?) wadi gravels', and by Beydoun (1980) as 'exhumed or fossil river channel systems'. In this paper the terms 'raised channels', 'exhumed channels' and 'palaeochannels' are adopted.

There is general agreement in these studies that the palaeochannels have been exhumed through differential deflation of fine-grained, poorly cemented interfluve sediments, while the well-cemented coarse-grained channel sediments have remained more resistant to deflation and hence have been preserved as upstanding ridges. Most of these workers consider that channel development occurred during a more humid climatic phase, with higher stream discharges associated with alternating wet and dry periods, or seasonal flows (Miller 1937; Butzer & Hansen 1968; Glennie 1970; Beydoun 1980). However, since channel-bed cementation appears to be occurring in the present-day arid environments

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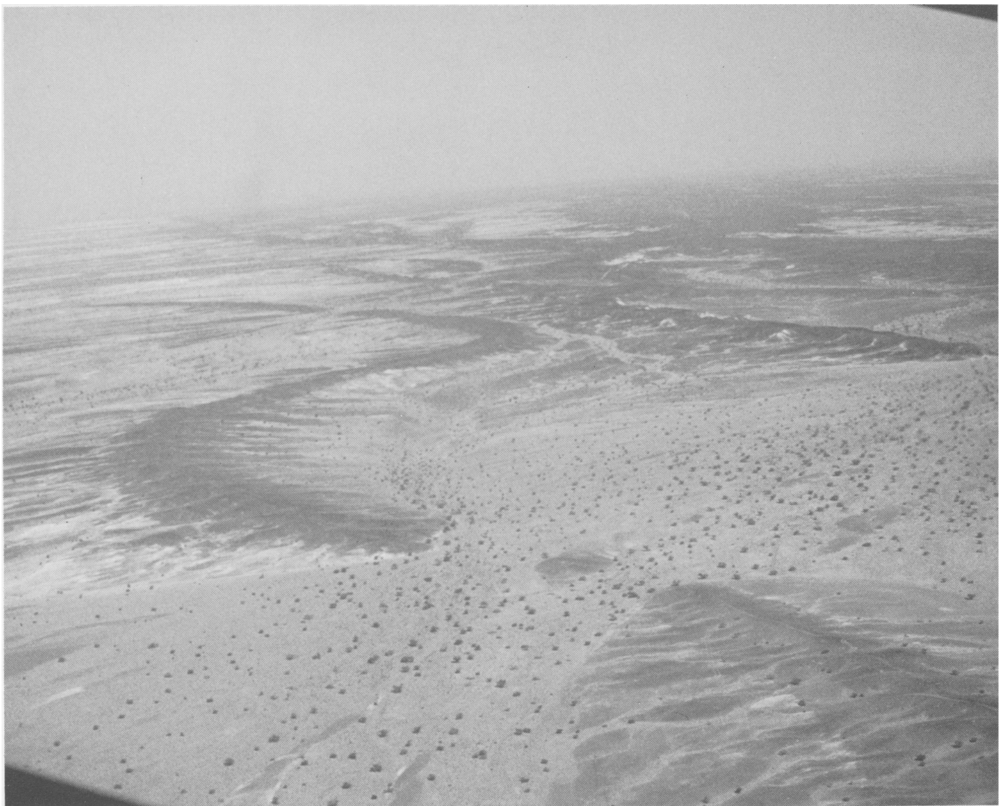


FIG. 1. Oblique aerial view of raised channel deposits overlying pink barzamanite. View looking SSW from Barzaman area.

FIG. 2. Ground view of thin Fan II gravels overlying weathered gravels and barzamanite of Fan I deposits. View looking N towards Barzaman and Jebel Madar.

of Oman, the link between climatic humidity and channel cementation remains uncertain (Gass pers. comm.).

However, there has been little consideration of the rates and patterns of fan development, nor any palaeohydrologic analysis of former alluvial environments, nor any consideration of the conditions either for channel exhumation or for fan entrenchment. No detailed morphological, stratigraphical or sedimentological analyses have previously been undertaken. The dates of channel formation are uncertain. Beydoun (1980) suggests that they may date from two wetter phases, identified by McClure (1976) in the Rub' al Khali, which occurred between 36 and 17 ka, and between 9 and 6 ka. However, Kassler (1973), Hötzl *et al.* (1978*a* and *b*) and Anton (1984) consider the vast sheets and ridges of alluvial gravels in central and eastern Saudi Arabia and Qatar to date from late Pliocene/Early Pleistocene sub-humid periods associated with high sea-levels.

Study area

Fieldwork was concentrated within the area of extensive alluvial fans W of the Wahiba Sands, which exhibits the most distinctive and complex systems of superimposed gravel ridges. The study area (Fig. 3) extends for *c*. 220 km from the foot of the Eastern Oman Mountains in the N towards the coast in the S, and for *c*. 50 km W–E, the western limit being marked in part by Wadi Halfayn. The eastern limit of the alluvial fan systems is marked in the N by contact with the Sands, and in the S by the abrupt western edge of the extensive aeolianite deposits that underlie the Sands (Gardner 1986).

Methods of study

The areal extent of the different alluvial fan systems was determined from *Landsat* imagery and partial air photo cover (at scales of 1 : 100 000, and *c*. 1 : 30 000). The thickness of the deposits was estimated from borehole records provided by the Public Authority for Water Resources (PAWR), Sultanate of Oman, as well as from field observations.

The surface morphology of the alluvial fans, the palaeochannels and the terraces was determined initially from mapping from the air photographs. Overall gradients were estimated very approximately from spot heights printed on the 1 : 100 000 topographic maps, although these were subject to regional height errors of up to 5 m. Ground surveys of the longitudinal- and cross-profiles of the channels and terraces were undertaken in two selected areas.

Sedimentary structures and clast fabric were recorded as palaeoflow indicators; coarse sediments were sampled for analysis of clast shape, size and composition as indicators of source materials, distances of transport, and post-depositional diagenetic alteration; and the mean intermediate diameter of the ten largest clasts was determined at each site for use in palaeohydraulic analysis. Samples of cemented sands and gravels were collected for petrographic and geochemical analysis. Lithological analyses and analysis of surface weathering characteristics were based on 100 surface clasts in the size range 16–32 mm from randomly located 0.5×0.5 m quadrats at over 300 sites.

Results

This paper summarizes the results of the field programme and preliminary analyses of the sedimentology, lithology and geochemistry and palaeohydraulics of the raised channel deposits.

Alluvial fan morphology

Two main fan systems have been identified from morphological, stratigraphical and lithological criteria (Fig. 3):

Fan system I is the oldest and most extensive, stretching southwards for *c*. 120 km from the foot of the Eastern Oman Mountains to the margins of the aeolianite outcrops in the S. PAWR borehole records (Aubel 1983; Jones 1986) suggest that buried gravels extend to depths of up to 285 m in some places, although these gravels also include the continental alluvial sediments of the Mio–Pliocene Upper Fars Group. This fan system slopes gently towards the S and SE with gradients decreasing from *c*. 0.0030 m m^{-1} W of Barzaman (Fig. 3) to only *c*. 0.0018 m m^{-1} in the SE, near the confluence of the Wadis Andam and Matam.

Fan System II forms a narrower, more recent channel system confined to the northerly, proximal parts of the present Wadi Andam piedmont zone (Fig. 3). The deposits are relatively thin, averaging only *c*. 8 m in thickness in the N (Jones 1986), thinning to only 2 or 3 m downchannel. The original channel gravels have been completely stripped off in some proximal areas, leaving undulating ridges of Hawasina chert bedrock. Many of the ridges of Fan System II rise 20–30 m above the adjacent wadi floors (Fig. 2). Proximal gradients are significantly

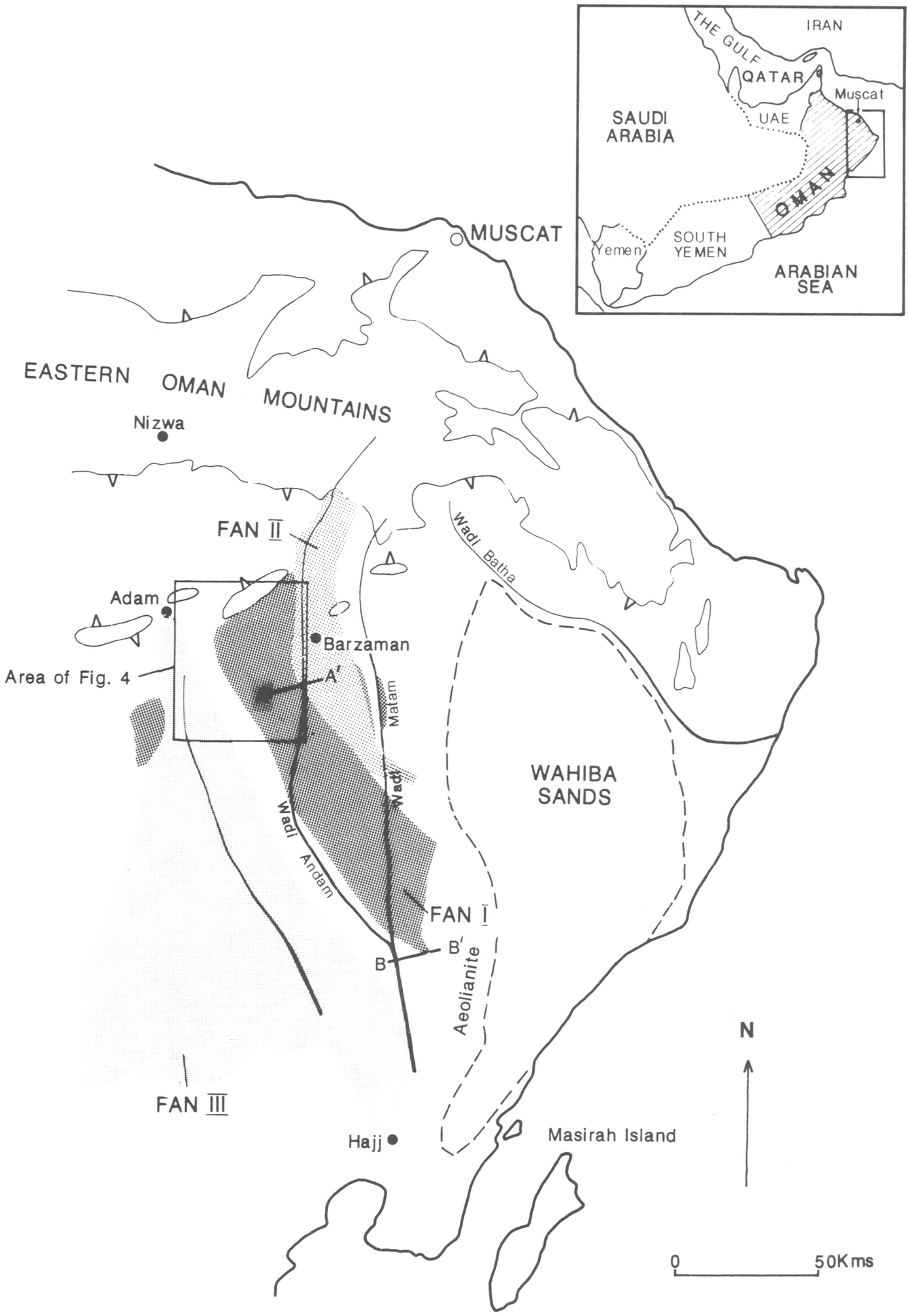


FIG. 3. Extent of main alluvial fans W of the Sharqiya (Wahiba) sands. A–A′ and B–B′ indicate locations of cross-sections in Fig. 8.

higher than on Fan System I, decreasing from *c.* 0.0046 m m^{-1} to *c.* 0.0028 m m^{-1} in the Barzaman area.

A third fan system was also identified to the W of Fan systems I and II; it extends for over 200 km from the mountain edge south southeastwards towards the coast. Apart from its low-gradient (*c.* 0.0005 m m^{-1}) distal channel systems, this fan lies beyond the study area.

Morphology of palaeochannel systems

The surface of *Fan I* is dominated by numerous sinuous low-relief (usually up to 5 m), linear gravel ridges exhibiting markedly undulating crestlines. Sinuosity often exceeds 1.5, where sinuosity is defined as the ratio of actual channel length to channel axis length. Many of these channels intersect or cross over one another, often with successive channels forming a series of superimposed channel deposits. The older channel courses in a superimposed sequence appear to have been significantly more sinuous than the younger channels (see below).

Many areas of Fan System I exhibit older, meandering channels overlain by straight channels (see Fig. 4). The oldest courses include channels with sinuosities exceeding 1.7, whilst younger courses exhibit sinuosities averaging only about 1.03. Meander wavelengths are highly variable, but preliminary measurements from the older sinuous palaeochannels indicate an average wavelength of about 2.1 km (Table 1).

Preserved channel widths are also highly variable, being represented by ridges ranging from only 20 m across, to broad flat-topped ridges up to 500 m across, and averaging about 120 m in width. Many of the original channel deposits have been dissected or truncated by later wadi or aeolian erosive activity, thereby reducing the width of preserved channel deposits. The extent of this modification appears, however, to have been relatively insignificant since numerous long and sinous channel courses can still be so clearly identified. In addition, if it is argued that channel-floor sediments have maximum preservation potential because of maximum cementation and maximum particle sizes, it seems likely that the preserved ridge widths are not significantly smaller than those of the former main channels.

The oldest channels often appear to be the widest, and exhibit similar widths in proximal and distal zones. By contrast, the youngest channels are relatively narrow (see Figs 4 and 5), and also appear to decrease in width in the downfan direction. It seems likely that these channels accommodated progressively smaller volumes of water downstream, as a result of transmission losses and evaporation.

Fan System II is characterized by high-relief (often over 10 m), low-sinuosity channels that rarely intersect or superimpose on one another, and which overlie Fan System I channel deposits (see Fig. 8*b*). The Fan II deposits include linear ridges, extensive gravel spreads, and sequences of terrace levels bounding the main wadi courses. Sinuosities average only about 1.03, while widths are relatively high, averaging over 700 m (Table 1), reflecting either formerly broad braided or sheet flood channels. Fan II palaeochannel widths decrease significantly downstream, with many channel courses tapering off from widths of over 400 m and disappearing within 6 km downstream. The Fan II channels largely disappear towards the SE as they approach the boundary of the Sands (Fig. 3).

Sedimentology of Fan System I

(a) Facies types

Four main facies types were identified in the Fan I deposits.

Facies type 1 comprises massive, poorly imbricated, clast-supported cobble gravels, with well rounded clasts (*eg* see Fig. 6) up to 20 cm in diameter. These gravels are interbedded with sediments of *facies type 2*, represented by finer grained sand and gravel units up to 3 m thick, which exhibit distinctive foreset and trough cross-bedded structures. *Facies type 3* comprises lenses of thin horizontally bedded, medium sand, and is of relatively minor significance. All these sands and gravels are cemented by clear crystalline calcite (see Figs 6 and 9) forming the matrix of the gravels and occurring as sparry calcite and crystalline crusts around individual clasts. Many of the fine matrix materials appear to have been replaced by the carbonate cement. *Facies type 4* is the most extensive. It generally underlies the sand and gravel facies types 1–3, but may be interbedded with some of these deposits. This facies comprises a whitish-pink, massive, indurated, fine-grained, dolomitic and clay-rich rock, here termed 'barzamanite' (Fig. 10). Preliminary X-ray diffraction analyses of barzamanite samples from a single site (see Fig. 6) indicate that the oldest material (sample 18.5) is largely dolomitic (Fig. 7). The younger deposits, by contrast, are rich in clay minerals, particularly illite, montmorillonite (samples 18.1, 18.3, 18.4, 18.6 matrix; see Fig. 7) and possibly palygorskite, together with small amounts of authigenic silica (see Watts 1980).

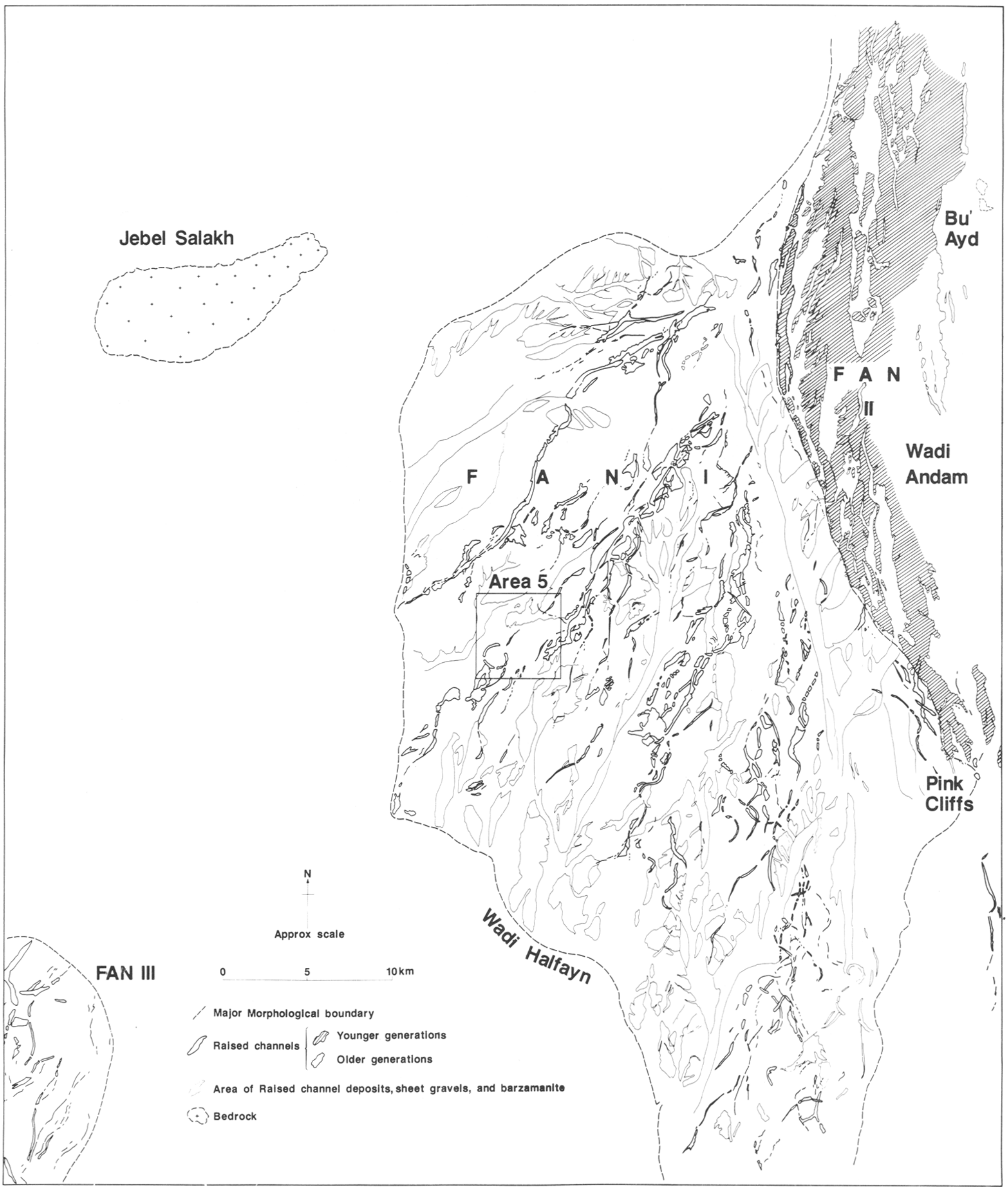


FIG. 4. Raised channel systems in the western area of Fan Systems I and II. Location shown in Fig. 3. Based on interpretation of 1 : 100 000 air photo mosaic.

Barzamanite often exhibits some sub-horizontal banding, a nodular structure; 'ghosting' which appears to reflect the positions of former clasts; and pockets and channels of gravels in different states of diagenesis. It often contains some small, isolated matrix-supported unaltered chert pebbles (Fig. 10). The pseudo-bedding of the barzamanite is often most distinctive towards the top of the profiles, where the barzamanite becomes increasingly nodular. At a number of sites the pseudo-bedding is deformed and exhibits either gentle large-scale folding or tight small-scale folds. Many features of the barzamanite facies resemble the characteristics of calcrete formation (Goudie 1983), although much of the barzamanite is dolomitic. Barzamanite deposits have also been recorded from further N in parts of Dubai (Bush pers. comm.).

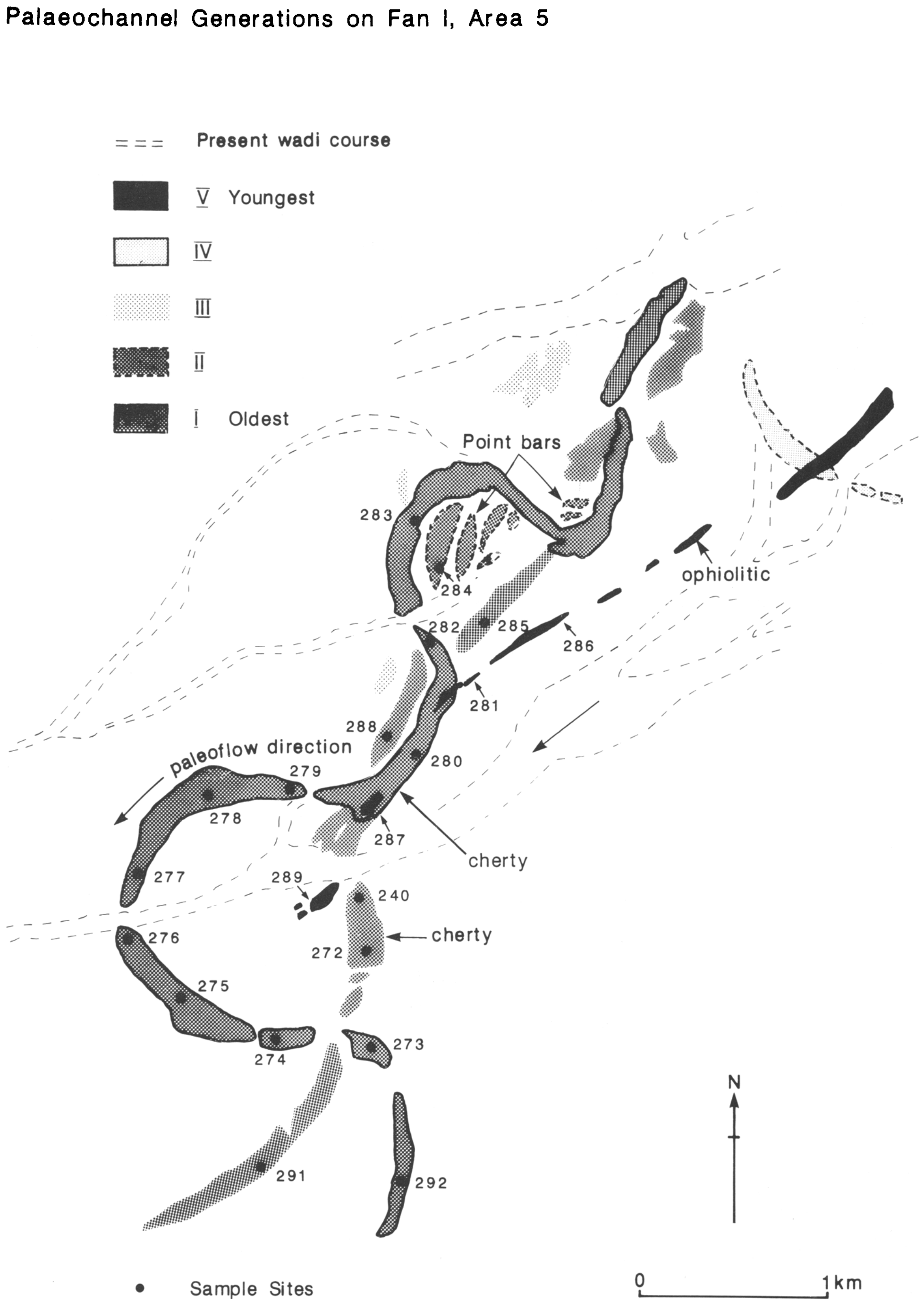


FIG. 5. Channel pattern and lithology changes associated with successive generations of palaeochannels on Fan I. Location shown in Fig. 4. Mapping based on 1:30 000 air photos, BKS Surveys Ltd, OM 85/49, 148 & 149.

TABLE 1. *Estimated palaeoflow parameters for selected raised channels of Fan Systems I and II, western Sharqiya, Wahiba, Oman*

Palaeoflow parameter	Equation no. (see text)	Fan I: Area 5 Channel generation (see Fig. 5)					Fan II: Pink Cliffs (see Fig. 4)	
		I (oldest)	II	III	IV	V (youngest)	High ridge (oldest)	Low ridge (youngest)
Gradient (regional)*				0.0044			0.0037	
Channel width m		108 ± 35	103 ± 34	80 ± 52	69 ± 11	49 ± 18	733 ± 351	1525 ± 318
Max. clast size cm		11.44 ± 2.12	12.07 ± 2.08	–	–	21.72 ± 2.69	15.14 ± 2.71	15.37 ± 4.73
Channel sinuosity		1.05	1.78	–	–	1.03	1.06	1.01
Meander wavelength† m		(2700)	2070 ± 525	(3000)	(2220)	(4650)	–	–
Radius of curvature† m		–	450	–	–	–	–	–
Flow depth m	2	2.4	2.5			4.6	3.78	3.84
Width/depth ratio		45	41			11	194	397
Cross-sectional area m^2		259	258			225	2771	5856
n_s	3	0.0272	0.0274			0.0302	0.0285	0.0285
n_L	4	0.0344	0.0347			0.0383	0.0357	0.0358
n_J	5	0.0354	0.0351			0.0319	0.0308	0.0307
f	6	0.0428	0.0428			0.0421	0.0405	0.0405
u_s m s^{-1}	3+8	4.38	4.50			6.04	5.19	5.23
u_L	4+8	3.46	3.56			4.77	4.14	4.17
u_J	5+8	3.36	3.52			5.72	4.79	4.86
u_f	6+9	4.40	4.52			6.12	5.21	5.25
u_c	10	1.81	1.86			2.47	2.07	2.09
Fr_s	1+3+8+11	0.90	0.91			0.90	0.73	0.73
Fr_L	1+4+8+11	0.71	0.72			0.71	0.46	0.46
Fr_J	1+5+8+11	0.69	0.71			0.85	0.62	0.63
Fr_f	1+6+9+11	0.90	0.91			0.91	0.73	0.73
Fr_c	1+10+11	0.37	0.38			0.37	0.34	0.34
Q_s	3+8+12	1137‡	1176‡			1350‡	14390	30624
Q_L	4+8+12	898	929			1066	11477	24424
Q_J	5+8+12	873	918			1278‡	13292	28425
Q_f	6+9+12	1142‡	1181‡			1368‡	14440	30717
Q_c	10+12	470	485			553	5752	12237
$Q_{CA}{}^+$	13	(2117)	1406	(2490)	(1566)	(4890)	–	–
Q_{SCH}	14	326	325	–	–	248	2490	4866
Q_{WW}	15	440	414	298	246	157	5304	13748
$Q_{WR}{}^+$	16	–	1284	–	–	–	–	–

Notes

* Measures of local channel gradients too unreliable;

† These measurements and computations only possible where well-preserved sinuous channels are present (unreliable values given in brackets).

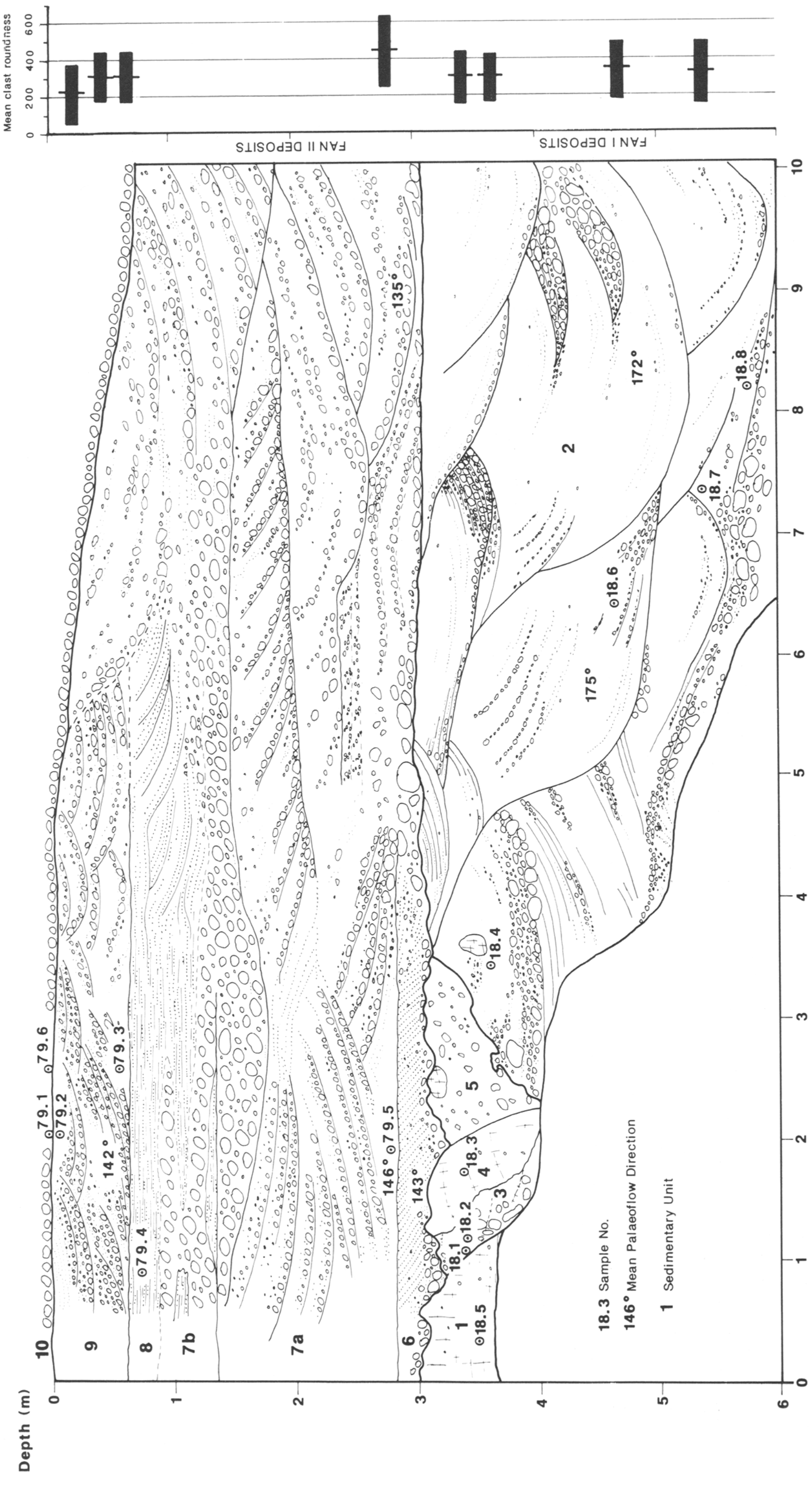
‡ Discharge estimates associated with Froude numbers between 0.75 and 1.0 (see text for explanation).

Subscripts denote use of equations as follows: s—Strickler (1923); L—Limerinos (1970); J—Jarrett (1984); f—Hey (1979); c—Costa (1983).

FIG. 6 (*opposite*). Stratigraphy and sedimentology of Fan I and Fan II deposits, site 18 near Pink Cliffs, Wadi Andam. A major unconformity separates the lower Fan I deposits from the upper Fan II deposits. The main sedimentary units are:

Fan II	*Unit*	*Description*
	10	Surface lag of black, varnished, ophiolite-rich pebbles < 16 cm dia., Cailleux roundness (R) = 225 ± 161.
	9	Trough cross-bedded gravels with isolated sand lenses; unaltered pebbles cemented by opaque clayey-calcite; palaeocurrent vector 125°; $R = 321 \pm 133$.
	8	Horizontally bedded fine sands.
	7b	Alternating sand and cobble beds.
	7a	Large cross-bedded sand units, coarsening upwards; $R = 449 \pm 186$.
	6	Planar and trough cross-bedded sands, fining upwards from a basal cobble layer; palaeocurrent vector 135°–146°.
	----	Unconformity

Fan I	*Unit*	*Description*
	5	Rubbly, structureless, poorly cemented barzamanite, with partially weathered ultrabasic clasts < 10 cm dia.; $R = 308 \pm 131$.
	4	Pseudo-bedded barzamanite, with a few scattered, bleached chert clasts < 1 cm dia.
	3	Poorly cemented weathered gravels, bleached cherts and ophiolites < 8 cm dia. in sandy matrix; $R = 309 \pm 132$.
	2	Trough cross-bedded sands and gravels, with cross-bed units < 1.6 m thick; included cobbles < 20 cm dia., in friable, white calcite cement; numerous weathered basic rocks; $R = 343 \pm 144$ and 335 ± 159.
	1	Barzamanite with partially weathered bleached basic clasts.


Mean clast roundness
0 200 400 600
FAN II DEPOSITS
FAN I DEPOSITS
Depth (m)
0 1 2 3 4 5 6
Distance along section (N to S) (m)
0 1 2 3 4 5 6 7 8 9 10
10
9
8
7b
7a
6
5
4
3
2
1
79.1
79.2
79.6
79.3
79.4
79.5
142°
146°
143°
135°
18.1
18.2
18.3
18.4
18.5
18.6
18.7
18.8
172°
175°
18.3 Sample No.
146° Mean Palaeoflow Direction
1 Sedimentary Unit

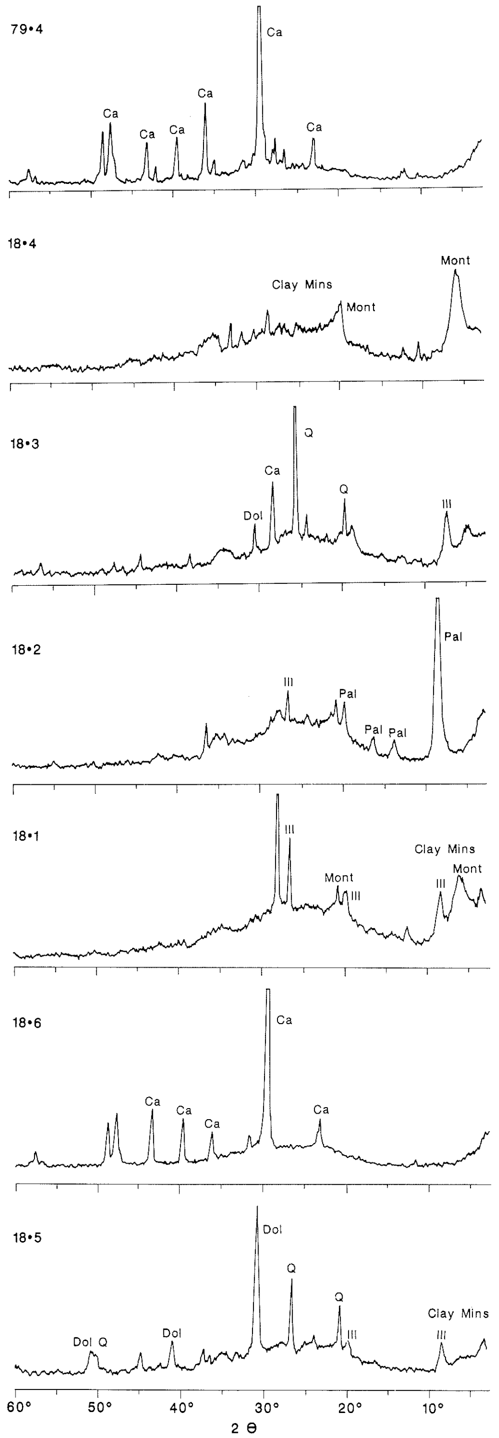


FIG. 7. X-ray diffraction traces for samples from site 18, Wadi Andam. Sample locations 79.4–18.5 shown on Fig. 6. Ca = calcite, Dol = dolomite, Ill = illite, Mont = montmorillonite, Pal = palygorskite, and Q = quartz.

(b) Sediment size characteristics

The gravels exhibit a wide range of particle sizes, normally forming a polymodal size distribution and hence a poorly sorted deposit. Maximum intermediate particle diameters exhibit a marked decrease over the 120 km of fluvial transport from *c.* 20 cm near the upland edge to only 5 cm downstream, representing an overall rate of size change of approximately 1.3 mm km^{-1}.

(c) Lithological composition

The gravels exhibit a wide range of lithologies, reflecting the heterogeneous nature of the source materials. The major constituents of the clastic fraction are: (i) *ophiolites*, which include serpentines, peridotites, gabbros and basalts, derived from the Semail Nappe outcrops in the Eastern Oman Mountains; (ii) *cherts*, derived from extensive Hawasina outcrops which bound the southern margins of the Oman Mountains. Cherts underlie most of the northern raised channel deposits, providing an abundant local supply of resistant materials for fluvial transport; and (iii) *limestones*, derived from a variety of sources of different ages, ranging from the older up-domed massifs (Permian–late Cretaceous), to the foothills of Hawasina turbidite limestones and 'exotic' marble (*eg* Hopson *et al.* 1981). A wide variety of other igneous, metamorphic and sedimentary rocks, largely derived from the Eastern Mountains, also occur within the gravels.

Significant differences in lithological composition of the gravels occur between channel deposits of different relative age. These differences reflect variations not so much in source of materials, but more in progressive post-depositional chemical alteration. The lowermost channel deposits, both in exposed sections and in superimposed palaeochannel sequences (Figs 5 and 6), exhibit the highest concentrations of cherts, usually occurring as unaltered or only partially altered, rounded and subrounded clasts. The ultramafic constituents, by contrast, appear to be most readily altered, and form much lower concentrations in the apparently oldest deposits. The barzamanite facies is often mottled by reddish-brown outlines or 'ghosts', possibly representing the diagenesis of former peridotite clasts to clay-rich materials (*eg* see Glennie *et al.* 1974, fig. 5.5*b*). The limestones also appear to exhibit progressive alteration and subsequent decreases in relative concentration.

(d) Surface weathering characteristics

Gravels exposed on channel surfaces exhibit evidence of desert varnish, case hardening and weathering rind development, of ventifacting

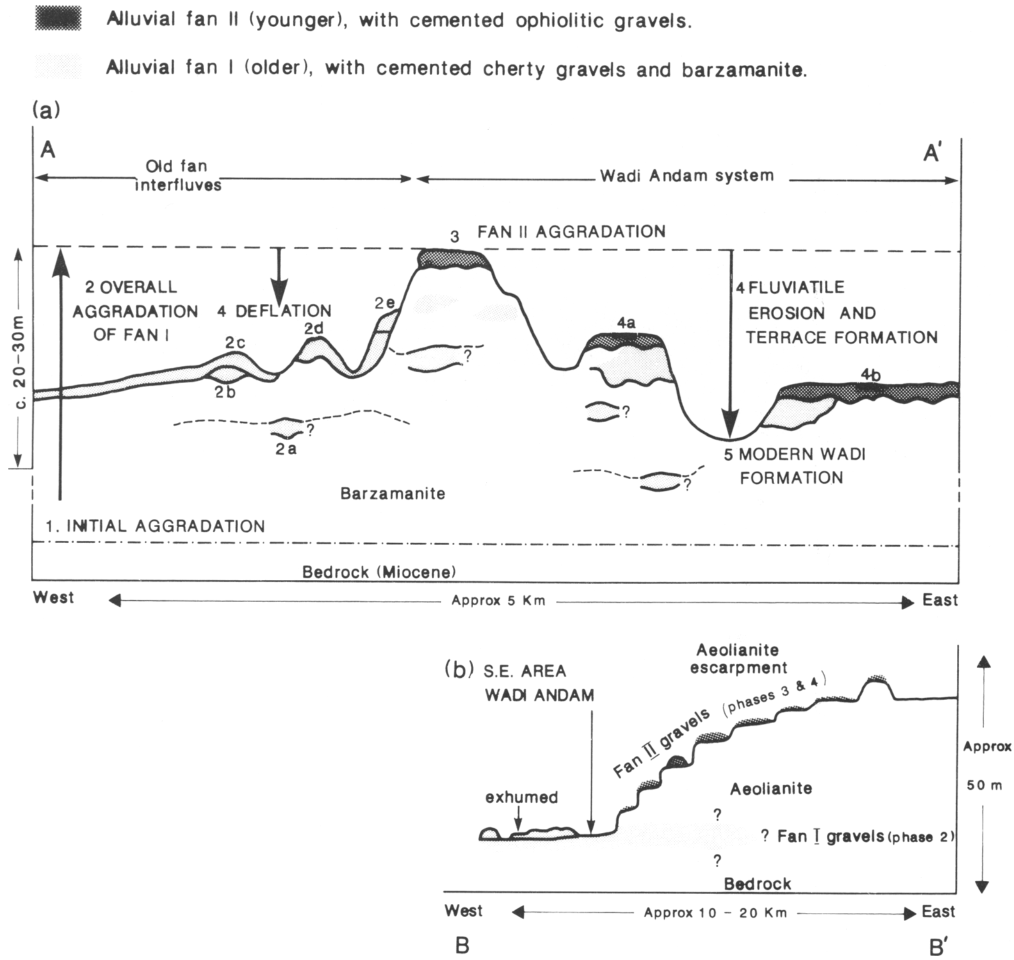


FIG. 8. Simplified model of landscape evolution of the alluvial fans and raised channel systems. (*a*) Cross-section A–A′ (see Fig. 3) across Wadi Andam at Pink Cliffs; (*b*) Cross-section B–B′ (see Fig. 3) SE of Wadi Andam across aeolianite escarpment. Phases of landscape evolution are denoted by numerals (see text for details).

and faceting, and of solution rilling and pitting, the latter particularly characteristic of limestone clasts. These clast surface features reflect long periods of subaerial weathering processes, including solution, dew etching, and aeolian sand abrasion. The gravels commonly form a layer of scattering only one particle thick (see McClure 1978) over barzamanite deposits, suggesting extensive removal of the former channel gravels by decomposition, solution, mechanical breakdown and deflation of the more basic and ultramafic lithologies. Many varnished surface gravels are underlain by 10–20 cm of clast-free silty sands and up to 50 cm of gypsiferous displacement and replacement growth (*eg* see Watson 1983).

Sedimentology of Fan System II

(*a*) *Facies types*

Two main facies types characterize the Fan II deposits. The dominant facies type, *type 5*, comprises coarse-grained (up to 0.5 m intermediate diameter) massive, cobble beds with little fabric or bedding. *Facies type 6* includes localized cross-bedded, coarse sand and fine gravel horizons. The two facies types are extensively cemented by calcite, but unlike the Fan I cements, those of Fan II appear to exhibit an opaque, clayey appearance with higher proportions of unaltered fine gravel particles in the matrix, and form a more friable and poorly indurated deposit.

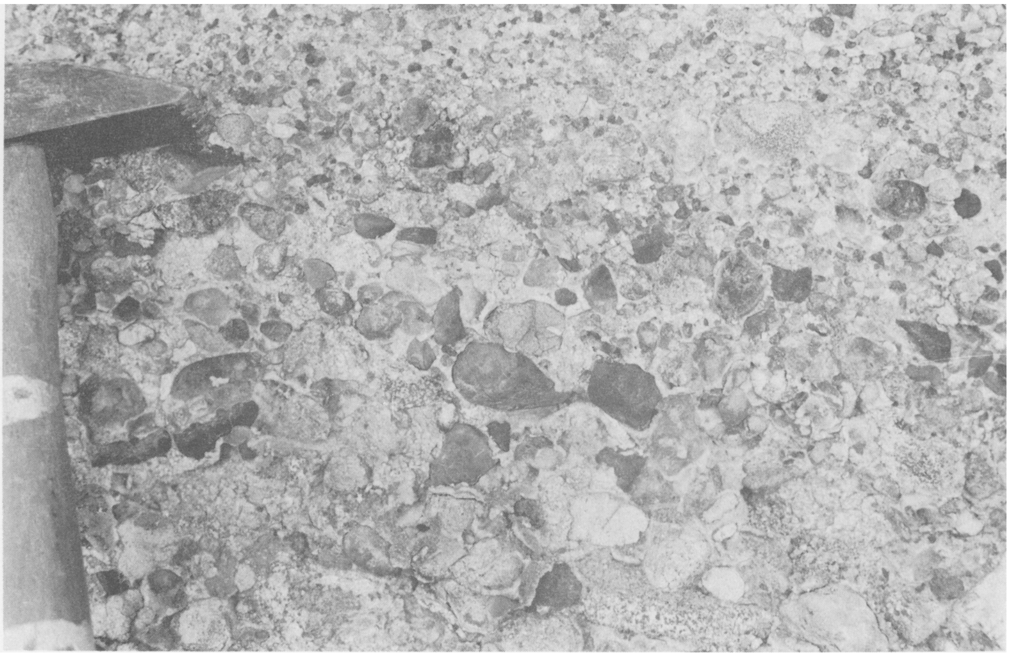


FIG. 9. Calcite crusts surrounding red-brown, chert-rich gravels of Fan I deposits, Site 18, Wadi Andam (see Fig. 6).

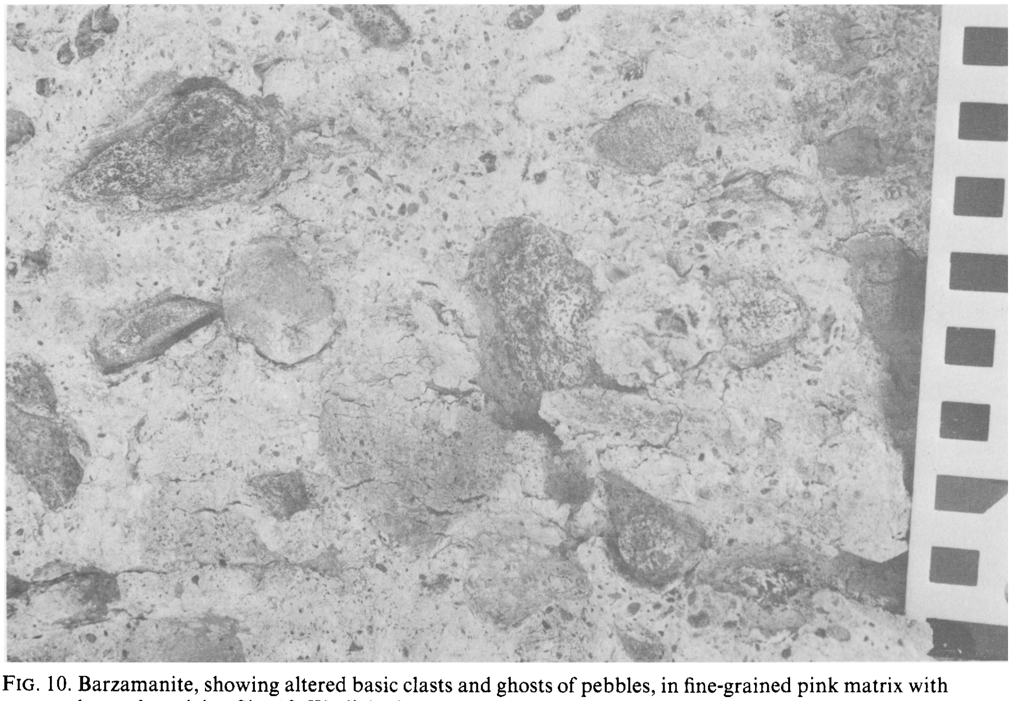


FIG. 10. Barzamanite, showing altered basic clasts and ghosts of pebbles, in fine-grained pink matrix with scattered gravel particles, Site 18, Wadi Andam.

X-ray diffraction indicates that the cement comprises a calcite–clay mineral mix (sample 79.4, Fig. 7).

(b) Sediment size characteristics

The Fan II gravels are poorly sorted. Maximum intermediate particle diameters decrease rapidly downstream, exceeding 40 cm in the proximal zone and reaching only 8 cm in the distal zone, representing an overall rate of size decrease of *c*. 5.5 mm km^{-1}.

(c) Lithological composition

The clast fraction of the Fan II gravels is dominated by well-rounded (*eg* see Fig. 6) gabbroic lithologies, with only minor percentages of cherts, limestones, serpentinite and other rock types.

(d) Surface weathering characteristics

The basic lithologies on the high channels and terrace deposits of Fan II exhibit evidence of extensive exfoliation, spalling and *in situ* splitting, processes that appear to be active at the present time. A major result of this rock disintegration is the production of a much finer grained surface deposit comprising increasingly small angular (see Fig.6) fragments and flakes of cherts and ophiolites, with progressive weathering. Surface clasts exhibit desert varnish, faceting and surface solution effects depending on lithology.

General stratigraphic relations

Fan II deposits overlie and are cut into the lower Fan I deposits along the Wadi Andam drainage system. The Fan II deposits are found at three main topographic levels (3, 4*a* and 4*b*, Fig. 8*a*) along Wadi Andam, with the lower two levels cutting into both barzamanite and channel gravels of the Fan I system. The contact between the two fan deposits forms a sharp, erosional boundary, often marked by a series of irregular, longitudinal flutes scoured into the underlying barzamanite (*eg* see Fig. 6). The boundary surface is generally coated with a thin microcrystalline layer of brown micrite (see Goudie 1983). Boulders of older cemented gravels and barzamanite are occasionally incorporated into the basal gravels of the younger Fan System II.

Palaeohydrology of the raised channels of Fan Systems I and II

(a) Channel pattern and sinuosity

Preliminary examination of the planform characteristics of successive generations of palaeochannels suggests that the older channel courses were significantly more sinuous than the younger. It thus appears that overall channel sinuosities have gradually decreased through time (see Table 1). Similarly, many of the older fluvial deposits appear to have been preserved as separate single-thread channels, while the more recent channels appear to have been associated with extensive sheet gravel formation, possibly associated with braided flows (see Fig. 4).

(b) Palaeoflow parameters

Sources of error. Preliminary estimates of selected flow parameters have been computed for some of the Fan I and Fan II palaeochannels. At this stage, however, there are still many uncertainties and sources of error involved in the application of palaeohydraulic models to the raised channel deposits. For example, estimates of former flow hydraulics including flow depths, resistance to flow, velocity and discharge for different palaeochannels have a number of input requirements including, in particular, estimates of the cross-sectional area of flow, former energy gradients, and maximum sizes of particles that the stream was competent to move. Accurate determination of these primary parameters may not prove possible for many of the palaeochannels. Overbank sediments have largely been removed, so that former flood flow widths can rarely be correctly determined. Former energy gradients can be estimated only very approximately from the published topographic maps. In addition, since many of the channels appear to have been considerably dissected, diagenetically altered and let down on to an underlying surface both by deflation to form a pebble lag and by compaction associated with diagenesis, the original channel gradients are unlikely to have been preserved. Maximum particle sizes, at least of the surface materials, appear to decrease through time by progressive granular disintegration, and hence measurements of maximum clast sizes may not always represent the largest materials that were originally transported and deposited in the channel. Details of some of the procedures adopted in the palaeohydraulic analysis of the raised channel deposits, and discussion of the many assumptions and sources of error involved in this approach are outlined elsewhere (Maizels 1983, 1986, 1987*a* and *b*). The procedures for estimating selected palaeoflow parameters are briefly summarized below.

Procedures for palaeoflow estimation. Two approaches have been adopted for determining former flow conditions.

The first approach is based on initial estimates of the critical shear stress at which bed particles begin to move. This computation uses Shields' (1936) function and allows subsequent calculation of former flow depth using the Du Boys equation (see details in Maizels 1983), and resistance to flow and flow velocity using Darcy–Weisbach and Manning equations. This approach requires the field determination of maximum particle sizes, in order to provide a measure of bed roughness, former channel gradients, and former flow widths. The main assumptions of this critical shear stress approach are the former existence of steady uniform flow; the validity of the shear stress model itself; a known effect of packing and imbrication on the Shields coefficient; the absence of local bedforms or coarse clast concentrations; and the availability of all particle sizes for transport by competent Newtonian fluid flows (*eg* see Costa 1984). Most of these assumptions remain questionable.

This critical shear stress approach allows the estimation of former mean critical flow depth, Y_c, from a form of the Du Boys equation, such that

$$Y_c = \tau_c/\gamma S \tag{1}$$

where τ_c is the critical tractive force (N m^{-3}) defined as

$$\tau_c = \phi(\gamma_s - \gamma)D \tag{2}$$

where ϕ is Shields coefficient (taken as 0.056), γ_s is the specific weight of the sediment, γ is the specific weight of water and S is the former hydraulic gradient.

The determination of palaeoflow velocities has depended on obtaining a measure of flow resistance using well-established friction coefficients for small-scale roughness in channels, namely, Manning's n and the Darcy–Weisbach f. Manning's n has been computed here from three different models.

Strickler (1923) derived a simple functional relationship between n and the representative particle diameter such that

$$n = 0.039{D_{50}}^{0.167} \tag{3}$$

where D_{50} = 50th percentile of the sediment size distribution. However, Limerinos (1970) demonstrated that n was best determined by the use of a logarithmic function relating the resistance coefficient to a measure of relative roughness (defined as the ratio of Y to D):

$$n = \frac{0.113 Y^{0.167}}{1.16 + 2.0 \log (Y/D_{84})} \tag{4}$$

where D_{84} = 84th percentile of sediment size distribution. More recently, Jarrett (1984) has derived a predictive equation for n based on multiple regression:

$$n = 0.32 S^{0.38} Y^{-0.16} \tag{5}$$

for $0.002 < S < 0.034$, $0.14 < Y < 2.01$ m, $0.028 < n < 0.159$, $0.09 < D < 0.79$ m.

The Darcy–Weisbach friction factor (f) has, however, a sounder theoretical basis as it is related to the von Karman–Prandtl velocity 'law', and is also dimensionally correct. Values of f were determined using the approach proposed by Hey (1979):

$$\frac{1}{\sqrt{f}} = C \log \left(\frac{aR}{D_s} \right) \tag{6}$$

where $C = 2.3/(\kappa/\sqrt{8})$, κ = the von Karman constant, and D_s = the representative grain size (m). The value of 'a' is a function of channel cross-sectional shape and spacing of roughness elements (Silberman *et al.* 1963), and may be determined either graphically (Hey 1979) or from:

$$a = 11.1(R/Y_{max})^{-0.314} \tag{7}$$

where Y_{max} = maximum flow depth (m) (Thorne & Zevenbergen 1985).

Once the resistance coefficients are computed, they can be substituted into equations for critical mean flow velocity u_c, based either on Manning's n, where

$$u_c = \frac{Y^{0.67} S^{0.5}}{n} \tag{8}$$

or on the Darcy–Weisbach f, where

$$u_c = \left(\frac{8gYS}{f} \right)^{0.5} \tag{9}$$

where g is the acceleration due to gravity.

Further estimates of mean flow velocity were determined from Costa's (1983) equation which is based on the mean of four theoretical and empirical functions:

$$u = 0.18(1000Y)^{0.487}. \tag{10}$$

The validity of the flow depth and palaeovelocity estimates was assessed by calculation of the Froude number, Fr, where

$$Fr = v/(gY_c)^{0.5}. \tag{11}$$

Froude numbers during high flows in coarse-grained gravel bed rivers rarely exceed values of about 2.5, and usually lie within 0.25 of the critical value of 1.0 (*eg* Boothroyd & Ashley 1975; Jarrett 1984; Bathurst 1985; Costa 1985; Thorne & Zevenbergen 1985). Palaeoflow depths and palaeovelocity computations that produced

Froude numbers within the range 0.75 to 1.25 were considered acceptable in this study.

Determination of palaeodischarge, Q, for the raised channel deposits was based on the flow continuity equation, where

$$Q = wY_c u_c. \quad (12)$$

The procedures outlined above for determining palaeovelocities therefore provided five different estimates of palaeodischarges, but each with error sources relating not only to field measurements but also to the validity of application of the various models themselves.

The second approach to the palaeohydrologic analysis of the raised channel deposits is based on the application of empirical discharge-form relations for meandering channels. These relations require determination of meander wavelength, L_M, radius of meander curvature, R_c, and bankfull channel width, w. Hence, major sources of error arise where former channel morphology is only partially or poorly preserved (*eg* see Ethridge & Schumm 1978; Rotnicki 1983). The equations adopted in this study are based on four empirical functions relating meander planform and channel morphological measures to discharge parameters.

Carlston (1965) (modified by Williams 1984) established an empirical relationship between meander wavelength and floods with a recurrence interval of 1.5 years ($Q_{1.5}$) for streams in the central USA, such that

$$Q_{1.5} = 0.011 L_M^{1.54}. \quad (13)$$

Schumm (1972) related channel width and maximum flow depth to bankfull discharge, defined as $Q_{2.33}$, for semi-arid and sub-humid channels in the USA and Australia, such that

$$Q_{2.33} = 2.66 w^{0.9} Y_{max}^{0.68}. \quad (14)$$

Estimates of flow depth calculated from equation (1) were substituted into Schumm's equation, while measurements of channel width and meander wavelength were taken from aerial photographs. Williams (1984) has provided two functions that relate channel width and meander radius of curvature to the maximum instantaneous discharge (Q), which more closely matches the types of discharges predicted by the critical shear stress approach. Williams found for meandering rivers in Sweden that

$$Q = 1.0 w^{1.3} \quad (15)$$

and that

$$Q = 0.28 R_c^{1.38}. \quad (16)$$

These relations provided four additional estimates of palaeodischarge for the meander channels, while only equations (14) and (15) were used for low-sinuosity channels. The two approaches to palaeodischarge prediction have allowed an envelope of discharge predictions based on nine different models to be produced for each of the raised channel systems.

Palaeoflow parameters associated with the raised channel systems. Palaeoflow depth, resistance, velocity, Froude number and discharge have been estimated for a number of raised channel deposits, while more detailed estimates have been made for successive generations of older palaeochannels in one area of Fan I (see Fig. 5), and for one area of Fan II channels bounding the present Wadi Andam (see Fig. 4 for locations). The results are summarized in Table 1.

Palaeoflow parameters of Fan I channel systems. Estimates of peak flow depths suggest that they averaged between about 1.2 and 4.5 m, although maximum depths may have exceeded 6 or 7 m in some channels during major flood events. Peak flow velocities averaged between about 2 and 7 m s^{-1} within the palaeochannel systems as a whole, with discharges ranging between about 160 and 1400 m^3 s^{-1}.

Palaeoflow estimates for successive generations of channels in 'Area 5' of Fan system I (Fig. 5, Table 1) are based on only approximate estimates of former energy gradients, derived from 1:100 000 topographic maps. This parameter probably represents the greatest source of error in the palaeoflow computations. Errors also arise in determination of former clast sizes, prior to weathering and rock breakdown, and measurement of channel width and planform characteristics from preserved channel fragments only.

The two earlier palaeochannel generations (I and II) exhibit significantly different channel form, sediment, and flow conditions from the youngest channel systems (V) in this area (Fig. 5). The earlier channels are at least twice as wide as the later channels, significantly more sinuous (system II), and comprise significantly finer clasts (representing long-term rock breakdown and/or finer sediments in transport). Predicted flow depths, and velocities were 30% to 85% greater in the younger, narrower, coarser-grained channels than in the broad sinuous, finer-grained older channels. However, because of similarities in cross-sectional areas of flow—the older channels exhibiting only marginally higher values—the peak discharges predicted for the different channels by the various methods are of a similar order of magnitude. The older channels were associated with palaeodischarges reaching about 1150 m^3 s^{-1} (with Froude numbers of about 0.9), while the younger channels were associated with those of about 1330 $m^3 s^{-1}$. Palaeodischarges predicted by the two approaches, at least for channel generation II, are also very similar in magnitude using equations (13) and (16).

Hence, significant changes in palaeoflow conditions appear to have occurred during fan aggradation. Palaeochannels became increasingly narrow, less sinuous, and probably carried coarser sediments; peak flow depths and velocities during flow events increased; while maximum discharges continued to be around a similar order of magnitude.

Palaeoflow parameters of Fan II channel systems. Fan II channel systems located at a similar distance from the mountain front as those examined on Fan I, exhibit significant contrasts with those of Fan I. In particular, the great widths of the preserved Fan II palaeochannel deposits, together with the nature of the constituent sedimentary structures and facies types (*eg* see Fig. 6), suggest that the deposits characterize broad braided channel systems. Estimates of peak flow depths of about 3.8 m suggest that width–depth ratios ranged between 200 and 400 (Table 1), almost an order of magnitude higher than in the Fan I channel systems. Channel gradients, particle sizes, flow resistance and velocity estimates are all similar in magnitude to those of the Fan I channels, but Froude numbers are much lower, suggesting that velocity estimates may be too low and/or depth estimates too high. The high palaeodischarges estimated by the different methods largely reflect, therefore, the broad lateral extent of the former channel systems. Peak palaeodischarges averaged between about 13 000 and 31 000 $m^3 s^{-1}$, according to most of the methods (particularly those with Froude numbers >0.7). The estimated peak flows therefore exceeded those of the Fan I channels by about one order of magnitude.

No detailed error analysis has yet been completed on these palaeohydraulic computations, but the palaeodischarge values were found to vary significantly according to the variability of the input parameters. For example, by varying each parameter by up to one standard deviation on either side of the mean in the case of S, w, and D and by varying ϕ values between 0.04 and 0.07 for the Fan II channels using equations (8), (9) and (10) resulted in palaeodischarge differences of up to $\pm 60\%$, $\pm 48\%$, $\pm 40\%$, and $\pm 67\%$, respectively. When these errors were combined, palaeodischarge values were found to range by up to 380% of the estimated discharges, although in this case the associated depth and velocity values appear excessively high (*ie* $Y_c > 7$ m, $u_c > 8$ m s^{-1}).

Although there are few records that extend over more than a 5-year period, the available flood discharge data for recent floods in the Sharqiya suggest that peak flow conditions in the Fan I palaeochannels as a whole may have been fairly similar to those of the present day. Estimates of width, depth and velocity during recent wadi flood events in Oman (Curtis 1985) ranged between 5–405 m, 0.28–6.19 m, and 0.006–9.72 m s^{-1}, respectively; while peak discharges reached *c.* 4650 $m^3 s^{-1}$. These discharges are significantly lower than those estimated for the Fan II channel systems.

Chronological framework

The relative ages of the different palaeochannel and alluvial fan systems have been established on the basis of morphological and stratigraphical relationships, together with preliminary observations of the different degrees of cementation and weathering within each system. Since the PAWR borehole data (Jones 1986) suggest that the older fan gravels overlie the continental alluvial sediments of the Mio–Pliocene Upper Fars Group in the N, and Miocene limestones in the SW (Aubel 1983), the earliest possible date for commencement of gravel accumulation appears to be early Pliocene.

The gravels are also found in association with the aeolianite that underlies much of the present-day Sharqiya sand sea. The older gravels of Fan System I extend southeastwards beneath the western edge of the aeolianite outcrop. Hence part of this older gravel sequence clearly predates the formation of the aeolianite. Patches of younger gravel, and a single raised channel ridge, have also been located on a series of 'terrace' levels across the aeolianite outcrop and along the edge of the escarpment (Fig. 8*b* and Warren *et al.* 1985). These deposits indicate that flows occurred at levels of up to 50 m above the present wadi floor. These gravels are likely to be related to the final stages of formation of Fan System I, followed by successive stages of incision and deflation to produce the stepped terrace sequence along the escarpment. This period of land-surface lowering may have been contemporaneous with the formation of the terrace sequence within the Wadi Andam Fan System II (Fig. 8*a*).

There are no directly datable materials available at present from the raised channels and alluvial fan sequences. However, examination of the nature and occurrence of chert artefacts on (but not within) the raised channel surfaces was carried out by Edens (1986). Intense concentrations of worked cherts occur on the older, lower channel ridges of the Fan System I near Barzaman

(Fig. 4). According to Edens (1986) the artefacts are likely to date from some time between 4000 and 7000 BP; these dates are in turn likely to represent the latest period during which palaeochannel exhumation could have taken place.

Palaeoenvironmental and landscape change

Landscape evolution in the area of the raised channels appears to have occurred in five main phases, possibly commencing during the early Pliocene.

Phase 1 is represented by the initial development of a large piedmont alluvial plain extending southwards from the mountain edge. The earliest deposits on this surface were probably associated with the final stages of uplift of the Eastern Oman Mountains, and are now recorded in deep boreholes, sometimes directly overlying Miocene bedrock, at depths of 250–300 m and at the base of Fan Sequence I (Fig. 8).

Phase 2. The initial development of a piedmont alluvial fan during Phase 1 was followed by a prolonged period of overall fan aggradation to form the Fan I deposit. This aggradational phase resulted in the infilling of the piedmont basin to depths of $\geqslant 200$ m with chert, ophiolite and limestone gravels from the Eastern Mountains. The lateral extent of this deposit was limited in the E by the presence of former sands, now forming the older aeolianites, although the eastern limit may have fluctuated through time.

Overall fan aggradation was associated with rapid cementation of the channel gravels through precipitation of calcite cements (Stalder 1975). The existence of a rising water table is indicated by the progressive long-term *in situ* chemical alteration of the gravel deposits, presumably lying near a rising water table. Gradually, the carbonate and ophiolite (especially serpentinite and peridotite) constituents of the gravels, together with the calcite cements and fine overbank and aeolian sediments, became altered or partially altered, to form the calcrete-like barzamanite deposits.

Progressive fan aggradation was accomplished by periodically rapid rates of sediment accumulation and by the successive development of new channels on the fan. Initiation of new channels probably occurred by blocking of channels with coarse sediments and aeolian sands, and by channel piracy and switching during high flow events.

It seems likely that substantial periods of time separated the development of successive channels during fan growth, since significant differences in the degree of weathering often occur in channels of different generations and at different elevations (Fig. 5). However, since some channels of different generations (*ie* with significantly different weathering characteristics) occur at the same elevations (*ie* with one channel ridge truncating a second), it seems likely that long-term fan aggradation was punctuated by periods of local channel downcutting into older channel deposits, allowing a new deposit to accumulate across its path.

Phase 3. The third phase of landscape evolution was characterized by a renewed period of fan sedimentation. These sediments represent the accumulation of thin (generally up to 3 m) ophiolite gravels of the Wadi Andam Fan System II. These younger gravels were deposited directly over the altered and partially altered older gravel of Fan System I. Distinctive unconformities and erosion surfaces mark the contact betwen the two deposits (Figs 6 and 8). The alluvial streams were very limited in extent compared with those of the older fan, disappearing southeastwards into the Sands.

Phase 4. The accumulation of the Wadi Andam gravels was followed rapidly by a phase of sudden and dramatic degradation of the fans (Fig. 8). Successive periods of large-scale incision of the Wadi Andam Fan System alternated with periods of thin gravel accumulation. Away from the wadi system and across the interfluves of the older fan systems, extensive lowering of the land surface took place. Along the Wadi Andam System, periodic incision was dominated by fluvial activity, resulting in the formation of two main terrace levels above the present wadi floor (Fig. 8). Up to 3 m of gravels were deposited on the terrace surfaces, unconformably overlying the older weathered gravel deposits and barzamanite of Fan System I (Fig. 6), and in more proximal zones, directly over bedrock. The weathering characteristics of the gravels on these terraces do not appear to be significantly different from those of the higher level gravels of Fan System II deposited during Phase 3 (above), suggesting that incision was accomplished relatively rapidly. Incision was also associated with relatively rapid lowering of the water table. Further S along the aeolianite escarpment, the lowering of the water table appears to have resulted in extensive deflation down to successive water table levels, forming a series of terrace surfaces (Gardner 1986). This deflation was accompanied by the occasional inundation by flows from the former wadi systems of Andam and Matam, initially extending for some 30 km to the SE. At times, more marked stream flow occurred closer to the wadi–aeolianite boundary, depositing channel sediments which subsequently became cemented and preserved as a raised channel ridge. In the interfluve areas of the fan deposits, land-surface lowering was accomplished largely by deflation, and only on a minor scale by water erosion. Extensive deflation of the barzamanite, the weathered cements, and the fine-grained matrix and overbank sediments resulted in the gradual exposure of formerly buried and diagenetically altered palaeochannel courses. Where successive palaeochannels had traversed the same areas of terrain, the younger channel deposits became exposed in a superimposed position over the older palaeochannels.

Phase 5. The final phase of landscape development is represented by the modern wadi system (Fig. 8). The modern Wadi Andam has cut into the Fan II deposits and continues to flow southwards towards the aeolianite escarpment, but now rarely, if ever, reaches the sea. There is little evidence of large-scale wadi channel modification or instability in recent times. In a number of wadi reaches, low terraces only 1 or 2 m high are found, and numerous bedrock outcrops occur in the floor of the wadi. These features suggest that the amount of incision and local sedimentation has been only minimal during periods of more recent wadi activity.

Palaeohydrological and palaeoclimatic implications of landscape evolution

Aggradation of Fan System I appears to have been associated with more sinuous channels, possibly related to less ephemeral flows than at present. Periods of flow extending for 2 or 3 months per year would probably have been sufficient to allow the development of an equilibrium relationship between the meandering channel planform and the associated channel capacity. However, peak discharges of some of the palaeochannels may have been of a similar order of magnitude to those of the present. Cementation of the channel gravels probably occurred soon after streamflow, and during periods of seepage and evaporation. The large-scale chemical alteration of the gravels would have required a high water table over prolonged periods of time, and hence is likely to have been associated with more humid conditions.

The formation of Fan System II and its subsequent sudden and deep entrenchment appear to have been associated with a more episodic, flashy flow regime. These flows may have occurred as intermittent periods of high flows acting to cut down through the fan deposits, followed by more stable flow conditions of sedimentary infilling or reworking. In addition, the apparent disappearance of the gravels into the Sands in the E may imply that semi-arid or arid conditions prevailed at that time. This period of fan downcutting was associated with a relatively rapid fall in the water table, possibly reflecting a combination of decreased sediment availability, decreasing climatic humidity, tectonic uplift and/or a glacial fall in sea level (Glennie pers. comm.). The extensive contemporaneous lowering of the interfluve fan areas is likely to have occurred during a period of increasing aridity, when sediments were exposed to wind erosion.

Chronological implications of landscape evolution

No dates are yet available for the older fan system, but the degree of widespread chemical alteration suggests that these deposits are likely to date from the Pliocene–early Pleistocene. Such a date would conform to the events proposed for this period by Hötzl *et al.* (1978*a*, *b*) and Anton (1984) for Saudi Arabia. In addition, aeolian sands and wadi gravels on the coast of Sabka Mati, Abu Dhabi, have been dated as early Pliocene (Glennie pers. comm.), suggesting that the period of alluvial fan aggradation in the Sharqiya could also have begun at this time. The hypothesis of progressively rising water tables during fan aggradation is further supported by the global rise of sea level during the Pliocene.

The overlying Fan II gravels are much younger since they are only minimally altered. Their relatively weak cementation may reflect either their relatively recent formation, or rapid downcutting, which cut off the supply of groundwater (Glennie pers. comm.). Their formation, and the period of fan degradation and land-surface lowering, probably date from arid and semi-arid phases of the mid- and late Pleistocene. The latest period of landsurface lowering and palaeochannel exhumation is likely to have been during the last glaciation (25 000 to 10 000 BP) when sea level is known to have been lower and desert winds are postulated to have been stronger (Glennie pers. comm.). According to the evidence provided by lithic components and artefacts, palaeochannel exhumation had virtually ceased by the early to mid-Holocene.

Conclusion

The model of palaeoenvironmental change proposed here invokes long-term fan aggradation during more humid phases (possibly during the

Pliocene and early Pleistocene), accompanied by cementation of the channel gravels and diagenesis of the ophiolite-rich and finer-grained sediments. Fluviatile entrenchment and landscape lowering by deflation of poorly cemented, fine-grained interfluve sediments appear to have occurred during subsequent alternating semi-arid and arid periods (possibly during the mid- and late Pleistocene). This model conforms with those proposed for Saudi Arabia by Hötzl *et al.* (1978*a*, *b*) and also for the Negev by Amit and Gerson (pers. comm.).

Many uncertainties remain in the model. In particular, the lithological, mineralogical and geochemical properties of palaeochannel sediments of different generations need to be determined in order to identify the temporal patterns of fan growth and channel evolution. Stratigraphical analysis of palaeochannel relationships also needs to be extended. Finally, the palaeohydrologic characteristics of successive channel systems need to be established more precisely, and possibly dated in order to be linked to likely patterns of palaeoclimatic change.

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